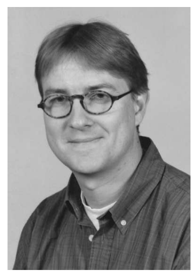
W MASS AND ITS UNCERTAINTY FROM MODELLING THE HADRONIC FINAL STATE AT LEP

K. RABBERTZ
EP Division, CERN, CH-1211 Geneva 23, Switzerland
e-mail: klaus.rabbertz@cern.ch



From 1996 up to 2000 the LEP collider at CERN has operated at center of mass energies above the production threshold for W boson pairs of approximately 160 GeV. The obtained data are used to extract a preliminary W mass value of (80.450 ± 0.039) GeV by direct reconstruction. To a large extent the uncertainty is due to systematic effects especially in the fully hadronic decay channel $W^+W^- \to q\bar{q}'\,q\bar{q}'$ that suffers most from ambiguities in modelling the hadronic final state. Methods to assess and reduce these uncertainties are the current main concern of the four LEP experiments.

1 Current Status of the W Mass Measurement at LEP

Each of the four experiments Aleph, Delphi, L3 and Opal has gathered around $700\,\mathrm{pb}^{-1}$ of integrated luminosity corresponding to about 10000 WW pairs per experiment. Depending on the decay products of the W bosons the possible configurations of the final state fall into three categories, the leptonic $W^+W^- \to l\nu\,l'\nu'$, the semi-leptonic $W^+W^- \to q\bar{q}'\,l\nu$ and the hadronic $W^+W^- \to q\bar{q}'\,q\bar{q}'$ channel with branching ratios of 11%, 44% and 45% respectively. Given reconstruction efficiencies of 80–85% and purities around 90% (80% for the hadronic channel) it is evident that the measurement of the W mass at LEP is dominated by semi-leptonic and hadronic WW events from which it can directly be reconstructed. The leptonic channel, which in addition suffers from the fact that it contains at least two undetected neutrinos in the final state, can merely serve as a cross-check. It is not affected, however, by uncertainties in the description of the transition from quarks to jets of hadrons (hadronization) and may become important in a future linear collider with very high luminosity. Final results from an Opal analysis [1] are given in table 1.[a]

[a] Note that the systematic uncertainty contains a statistical component and would shrink with higher integrated luminosity.

Table 1: Decomposition of the W mass uncertainty for the final OPAL analysis of the leptonic decay channel and for the preliminary LEP combined results of the semi-leptonic and hadronic channels. Detector systematics include uncertainties in the jet and lepton energy scales and resolution. The "Other" category refers to sources of uncertainty largely uncorrelated between the experiments like event selection, fitting method, background estimation, simulation statistics or four-fermion treatment.

	ΔM_W/MeV			
Data	O final	LEP ADLO Preliminary		
	$l\nu\, l'\nu'$	$q\bar{q}'\, l\nu$	$q\bar{q}'\, q\bar{q}'$	Combined
LEP Beam Energy	11	17	17	17
ISR/FSR	7	8	9	8
Detector Systematics	115	12	8	10
Hadronization	-	19	17	17
Colour Reconnection	-	-	40	11
Bose-Einstein Correlations	-	-	25	7
Other	52	4	4	3
Total Systematic	127	29	54	30
Statistical	410	33	30	26
Total	430	44	62	40

For the hadronic WW events additional complications arise with respect to the semi-leptonic ones because of ambiguities in the assignment of jets to W's on the one hand and possible cross-talk either between the quarks from different W's before the formation of hadrons due to colour reconnection (CR) or Bose-Einstein correlations (BEC) between identical bosons on the other hand. This leads to the unpleasant fact that despite a larger statistical weight of 55% compared to 45% the hadronic channel contributes only to 27% to the final combination. The latest preliminary results on the W mass and its uncertainty from a combination of all four LEP experiments ADLO [2] can be found in fig. 1 and table 1. Obviously, it is worthwhile to look for a systematic bias on M_W due to additional final state interactions possible in the hadronic channel. To date, no significant discrepancy between $M_W^{\mathrm{non-4q}} = (80.448 \pm 0.043)\,\mathrm{GeV}$ and $M_W^{\mathrm{4q}} = (80.457 \pm 0.062)\,\mathrm{GeV}$ has been found: [2] $\Delta M_W(\{\mathrm{4q}\} - \{\mathrm{non-4q}\}) = (+9 \pm 44)\,\mathrm{MeV}$.

In the following, the effects of colour reconnection and hadronization will be discussed in more detail, Bose-Einstein correlations are covered elsewhere.[3]

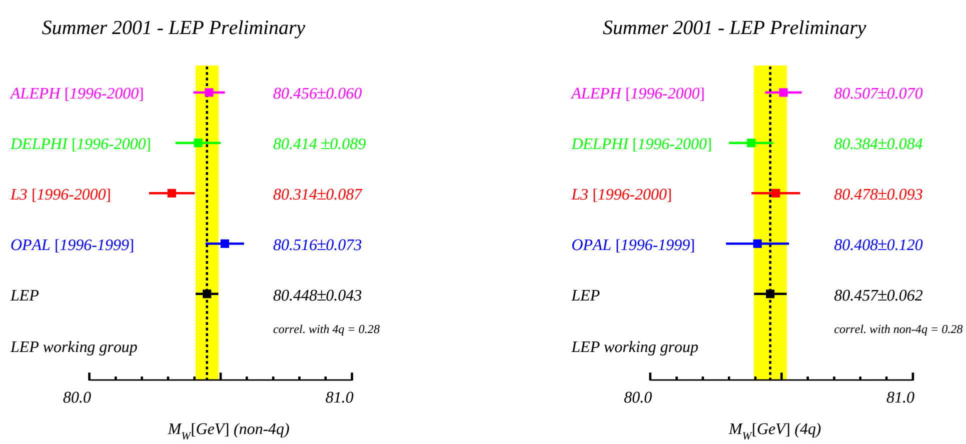


Figure 1: Preliminary W mass measurements from LEP

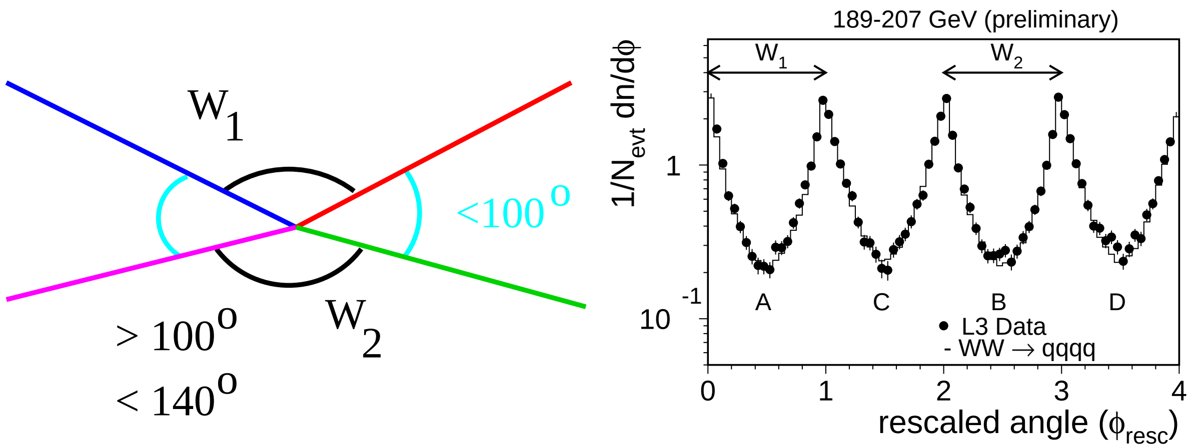


Figure 2: A sketch of the additional requirements in the topological selection (left) and the particle flow with respect to the rescaled angle from L3 (right).

2 Colour Reconnection

Since a theory that precisely describes the transition from coloured partons, i.e. quarks and gluons, to colourless hadrons is currently not available, one has to rely on phenomenological models of the hadronization process. In the context of W pair production and the subsequent decay into four quarks, interactions between quarks from different W's are possible due to the smallness of the separation between their decay vertices (O(0.1 fm)) with respect to typical hadronization lengths of O(1 fm). Hence, there is no unique assignment of hadrons to W's which may systematically influence the direct reconstruction of the W mass. In terms of models that have been suggested (Sjöstrand-Khoze or SK, ARIADNE, HERWIG, Rathsman) the colour forces strung between the partons may be reconnected if it leads to a more favourable configuration according to a model-specific prescription. Effects may be observed e.g. for particle multiplicities, inter-jet particle distributions and, unfortunately, for the W mass itself.

Apart from the latter the inter-jet particle flow method, pioneered by L3,[4] is one of the most sensitive so far. Compared to the selection requirements for the W mass analysis more stringent cuts on the jet properties are imposed here (see fig. 2 left) leading to a cleaner jet topology at the expense of an efficiency as low as 12%. Currently, Delphi and L3 employ this topological selection whereas Aleph and Opal prefer to stick to their standard one.

Starting from the most energetic jet and continuing via the second jet attributed to the same W to the two jets of the second W, in total four inter-jet planes are defined. Each particle is projected onto all four planes and is assigned to the plane with which it makes the smallest angle. It is included in the particle flow if the projection lies between the two jets connected by the corresponding plane. After a rescaling of the angular distance to the jet defining the start of the plane the particle flow can be shown as in the example from L3 in fig. 2 right.[5] Effects of colour reconnection can now be searched for in the form of differences between the flow in intra-W regions A and B and inter-W regions C and D with and without CR.

Figure 3 left from Aleph [6] shows the ratio of the particle flow in the intra- and inter-W regions for data and three MC files with 0% (full), 70% (dotted) and 100% (dashed) reconnections for the SK I model. The extreme case of 100% reconnections is disfavoured but values up to 80% seem to be consistent with the data. To focus on the region away from the original jet direction the integral R_N from 0.2 up to 0.8 is used to extract the numbers in fig. 3 right.[7] The more stringent selections employed by Delphi and L3 seem to exhibit smaller reconnection effects but within current uncertainties a clear conclusion can not be drawn. A large LEP-wide effort is now going into the production and simulation of common MC files for all four experiments in order to address the problem of a consistent combination of the individual results.

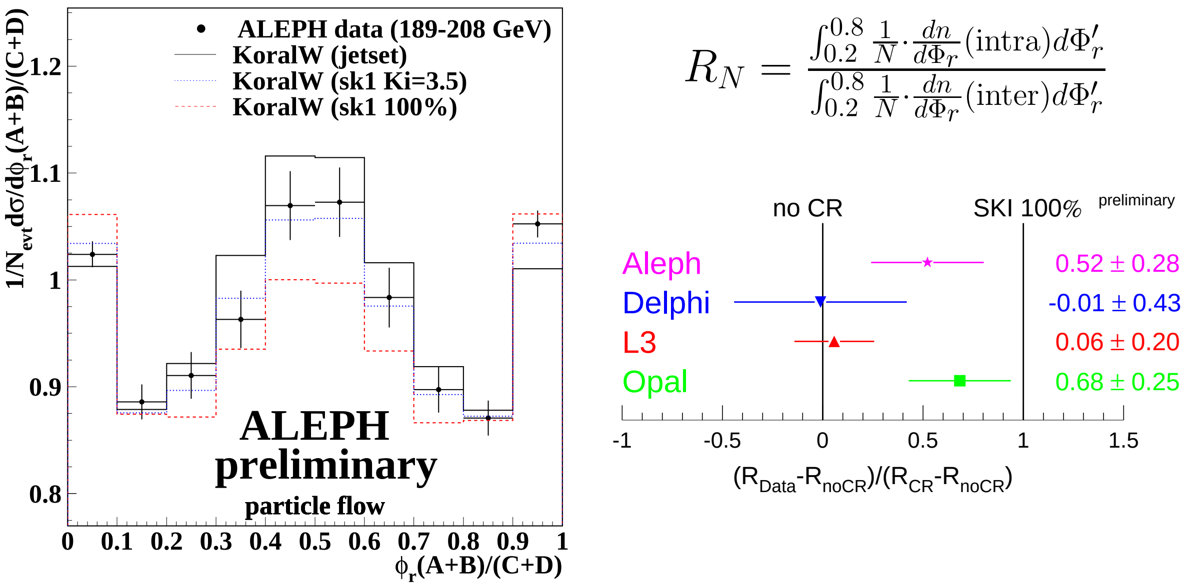


Figure 3: Ratio of intra- to inter-W particle flow from ALEPH (left), definition of integrated ratio R_N and ratio of its offset with respect to a no CR scenario for data and MC (right).

3 Hadronization

Table 1 demonstrates that the modelling of hadronization is a large uncertainty even without additional complications like colour reconnection, and it is the dominant one that is in common for the semi-leptonic and hadronic decay channels. Individual estimates by the experiments using the Jetset, Ariadne and Herwig MC's vary for this uncertainty from 15 MeV up to 30 MeV. Also here the common MC files will be used to address the somewhat incoherent picture, which is partially due to different MC tunings used for the individual experiments.

4 Summary and Outlook

The current preliminary LEP combined value for the mass of the W boson is [2]:

$$M_W = (80.450 \pm 0.039)\,\mathrm{GeV}.$$

A large part of the total uncertainty is due to the necessity to use phenomenological models for the hadronization process in general and for colour reconnection in particular. Ongoing efforts in the LEP community aim at a better understanding of the common problems in order to achieve improved and consistent results that can be combined to reduce the W mass uncertainty on the one hand but also to learn something about the possible existence of final state interactions. There is more to come soon.

References

1. The OPAL Coll., G. Abbiendi et al., hep-ex/0203026, CERN-EP/2002-022, submitted to *Eur. Phys. J.* **C**.
2. The LEP Colls., the LEP Electroweak Working Group and the SLD Heavy Flavour and Electroweak Groups, hep-ex/0112021, CERN-EP/2001-098, unpublished.
3. T.H. Kress, *Particle Correlations in Z and WW Events*, these proceedings.
4. D. Duchesneau, LAPP-EXP 2000-02, *Nucl. Phys. Proc. Suppl.* **96** (2001) 13.
5. The L3 Coll., L3 Note 2683, submitted to ICHEP, Budapest, Hungary, 07/2001.
6. The ALEPH Coll., ALEPH 2001-047, submitted to ICHEP, Budapest, Hungary, 07/2001.
7. P. Abreu, *Colour Reconnection at LEP2*, hep-ph/0111395, to be publ. in the Proc. of ISMD, Datong, China, 09/2001;
   A. Straessner, private communication.